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IMPORTANT STRUCTURAL RESEARCH PROBLEMS FOR THE SUPPORT OF FUTURE SPACE MISSIONS

Prepared by Lewis H. Abraham in collaboration with
the NASA Research Advisory Committee on Missile
and Space Vehicle Structures

NASA Headquarters
Washington, D.C.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

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The purpose of this report is to delineate and predict the structural research problems which can be viewed as technically or economically of major significance to missile and space vehicles planned or envisioned for the time period of 1970 to 1980.

This report suggests general areas of research and, where possible, specific areas in which research effort should be concentrated in order to provide necessary information and understanding for the design of missile and space vehicles and necessary support equipment for this era.

INTRODUCTION

The variety of missions, vehicles, and types of structures to be contemplated for the 1970's is legion and presents innumerable design problems. It is the task and obligation of the Research Advisory Committee on Missile and Space Vehicle Structures to define these problem areas in the structural field and so to meet the technological challenge and demand, ever widening in complexity, of future vehicles and missions.

This report avoids discussions of many of the generic problems that have been adequately covered by previous works. Rather, members of the committee feel that the future problem areas outlined herein represent their best estimates of specific diciplines in the field of structural research where technological advancements must be made in order for this nation to maintain a position of preeminence in space exploration. It is hoped in stating these problems that researchers will receive guidance in selecting areas wherein their particular talents may be applied to best advantage for maximum reward.

No attempt is made to establish priority or relative urgency of the research problems covered in this report. Any such attempt would be moot and if followed to the letter could dislocate talent to the serious detriment of the total effort.

Likewise, minor discoveries within one segment of a particular field can be transferred to the other fields and often will be helpful in uncovering still further knowledge.

While the primary interest of this report is to expose problem areas where research support is necessary to meet the challenge of the missions of 1970-1980, it must not be construed that these solutions will not be useful prior to that decade. In most instances earlier solutions could advance the date of feasibility of some missions. Certain intermediate operations might even be eliminated by important advancements.

This report may appear premature in exposing some of the problem areas which may not be encountered for several years. This timing is not inconsistent, however, with lead time requirements of planning, funding, and implementing of test programs. These phases must be considered now.

ANTICIPATED OPERATIONAL REQUIREMENTS

Near-earth orbital operations are already underway, and rendezvous operations in space are now planned. Manned space stations are under consideration. Operation of one or more large orbital space stations, with frequent travel between stations and earth, is contemplated during the time period of interest. These operations would include the more difficult 24-hour synchronous-type orbits.

Lunar manned reconnaissance and landing operations are already planned. By 1970, man will have initially explored the moon's surface and will be ready for long-term exploitation of these initial explorations. The size and frequency of these operations will increase and lead to the establishment of lunar stations in the 1970's. Lunar vehicles will be required to transport the variety of supplies necessary for maintaining a manned base and the vehicles will inevitably increase in size as fast as the advancement of the technology permits. In addition, a variety of support vehicles for lunar exploration, transportation, and construction will be developed.

Earth launched vehicles will grow in size, and economic reasons will dictate the development of reusable types. Entry velocity into the earth's atmosphere will of necessity steadily increase, foreseeably reaching above 50,000 ft/sec. Greater maneuverability requirements will further complicate the technology. With greater maneuverability, a choice of landing sites will be available, requiring varying alighting and arresting gear. Nuclear power plants and some electrical propulsion schemes will have been tested and will be available for introduction into operational vehicles about the turn of the next quarter century. This event will create many new structural and material problems.

Planetary unmanned reconnaissance and landings are already well into the planning stage. Manned reconnaissance, landing, exploration, and establishment of bases on the planets will be planned in the period 1970 to 1980. Manned exploration of Mars and Venus will possibly be attempted first, possibly toward the close of that decade. Planetary missions will require a complete range of vehicles for extraterrestrial atmospheric entry, landing, surface and atmospheric exploration, and launching for return to earth.

In addition, spacecraft will require certain fixed-base equipment peculiar to their specific operations. Large communication antennas that may be used on earth, on a remote planet, or even on the spacecraft itself must parallel the development of the space vehicles. Highly accurate large parabolic surfaces will be required for use on the earth, the moon, the planets, and in spacecraft as communication antennas, as optical and radio telescopes, or as solar energy collectors. Structural problems involved in getting the required accuracy and maintaining it under various environmental conditions are considerable. In addition, difficult structural dynamics problems arise in the control and pointing of these structures.

A variety of structures and shelters for use on the moon or the planets will be required. Each of these must be designed to withstand the environmental conditions of launch, space flight, landing, and subsequent exposure to the surface, subsurface, or atmospheric environment of the planet on which it is to be located. Maximum use must be made of local materials.

Scientific responsibility demands that any landing on the moon or the planets be done by sterile vehicles. This will prevent contamination of the primeval environments. Similarly, for protection of earth inhabitants, sterilization of returning vehicles will be required until it is established that there is no danger from introduction of alien microbes, plants, spores, or harmful vegetation. Techniques for accomplishing complete sterilization before take-off and prior to reentry must be further developed.

The multitude of missions and the use of new and unusual components such as nuclear reactors, electrical propulsion systems, and large solar-collection and heat radiation devices on spacecraft will introduce unique and difficult static and dynamic structural problems. Functional components of the vehicle, such as thermal control systems, heat radiators, solar concentrators, entry heat shields, insulation, space hazard shields, landing impact absorption systems, and propulsion systems are all major weight items that are also potentially useful as load-carrying structure. Design procedures must be broadened to make structural use of these functional and environmental devices.

Manned space flight beyond low earth orbits will require shielding against ionizing radiation. Passive shielding with a large mass of material is increasingly unattractive and appears impractical. Development of active systems and associated structure will be required if manned missions in the 1970's are to proceed without severe restrictions.

ENVIRONMENTAL CRITERIA FOR THE DESIGN OF FUTURE SYSTEMS

Determination of the characteristics of the environment that the structure must survive is one of the most important factors in defining structural problems and seeking their solution. Many structural design problems result from an inadequate knowledge or definition of these characteristics. This is further complicated by the variety of mission requirements, which results in differences in type of environment, and in severity of duration of exposure.

Protection from meteoroids has a large influence on structural design. The most urgently required data are penetration rates for engineering materials of known thicknesses. Direct measurements of penetration rates for very thin materials can be attained from satellite experiments of reasonable size and duration. Such experiments are underway for the evaluation of the meteoroid hazard in the near-earth field. The direct measurement of penetration rates for materials of thicknesses considered necessary for the protection of large space radiators is questionable, however, because of the extremely large surface that would have to be deployed in the space experiment to obtain a statistical penetration rate in a reasonable time. This would indicate the necessity of evaluating the meteoroid hazard by less direct methods. Added research will be required to deduce the frequency, size, composition, and velocity of meteoroid particles from radar and photographic measurements. Penetration data need to be determined for various vehicle surface orientations relative to the ecliptic and to the earth's velocity vector.

In addition to data on the near-earth hazard, data are required for hazards in the vicinity of the moon and out to the nearer planets. Ultimate usefulness of these data would be the establishment of a design criteria that would be related to the survival probability of the vehicle.

In order to intelligently predict penetration, the theory and mechanisms of penetration must be better understood. Consistent penetration prediction methods will have to be developed that cover the entire range of material thicknesses of interest. In addition, design methods for meteoroid protection must be developed. Considerable research is being conducted on protection systems, but little has been done in establishing design principles for providing protection systems for various components of space vehicle systems.

Facilities for accurate simulation of the meteoroid environment must also be developed. Existing facilities, at best, can only simulate the lower range of the estimated meteoroid velocity spectrum.

High priority must be given to programs that measure the properties of particles and wave phenomena in space. This would include measurement of the composition, density, temperature, and motion of planetary atmospheres. The composition, roughness, hardness, and temperature of the lunar and planetary surfaces must be determined before efficient design of alighting gear can proceed.

As engine thrust increases, the power of the engine noise shifts to the lower frequencies, and as vehicle size increases, buffet-load frequencies decrease as well. These sources of low-frequency input can cause structural as well as other problems (e.g., control coupling of low-frequency vibration). In addition, responses to these inputs that can be felt by the crew will be required to be small. At present, no suitable technique exists for predicting the vibration environment for a given vehicle configuration in various flight regimes. Vehicle shapes, trajectory, and environmental characteristics are all involved.

Research should be directed toward the development of design environment spectra for each basic mission and each type of vehicle. These spectra should encompass the total useful life of the vehicle, define the critical environmental effects, and establish sequential order of occurrence and severity and duration of exposure.

STRUCTURAL RESEARCH

Analysis Methods

Structural analysis problems undoubtedly will arise in developing new criteria for many future, yet undefined, design configurations. Structural load analysis techniques will probably keep abreast of the advancement of the technology and will offer no serious problems. On the other hand, analysis techniques for defining the actual environment and its effects, and for predicting the life and extent of the usefulness of the structure could easily fall far behind present methodology. Analytical prediction techniques for the useful life of a structure are even now only fair. The very near future portends even larger errors and complications. The far-future trend indicates even greater complexities. It has been suggested, for example, that a total strain criterion might be a rational approach for reusable reentry vehicles. It is also conceivable that a criterion which relates structural weight to the degree of risk might be a rational approach for a manned space system. The old factor-of-safety concept will have to be abandoned if future structures are to become more efficient. This refinement awaits research which will produce procedures whereby structural integrity will be based upon component and total vehicle reliability rather than arbitrary factors of safety.

Most of our present-day criteria experience has been with missiles and manned systems operating in the atmosphere, where loads, stress levels, and required lifetimes have been major considerations. We now face the space environment, where the incidence of traditional loads and stress levels will be small, except for the launch and recovery phases of the mission, and environmental protection requirements will be large.

On the first launching of many vehicles there will be reliability requirements exceeding anything in practice today. Missions may last for years with little or no chance for repair. Research directed toward establishing this degree of reliability is essential.

The basic problem of deciding whether a particular component or system design is satisfactory must be approached differently in the development of future vehicles and systems. The most promising approach involves the use of reliability analysis and decision theory. However, this approach requires specific statements of utility (or tradeoff in weight, performance, useful life, cost, etc.) and degree of risk, and also requires that environmental data, loads, and strengths be expressed in terms of means and deviations rather than maximums and minimums. Greater reliability through better understanding of instability failures and fracture mechanisms offers a wide vista for research. A good start would be the development of basic analytical methods and procedures to formulate the statements of design criteria and utilities, and to integrate these with the acceptance criteria.

Economic Aspects of Structural Design

Boosters required for future space missions (beyond those capable of achievement with the Saturn class rocket) will pose a significant economic problem due to size alone. The present technical approach to booster system development may well result in costs which are prohibitive. A close and careful examination should be made of the technical aspects of fabrication, testing, transportation, and erection of large boosters from the standpoint of what can be done to reduce costs.

Past trends in structural improvement have led to lower weight but often at higher cost. More consideration should be given to development of efficient structures that are also less costly, less complicated, and more reliable. Structural optimization procedures should be derived which evaluate the relative merits of alternate approaches on the basis of least total cost in the performance of the flight mission.

Novel structural concepts to improve structural efficiency and save weight should be investigated; for example, the cellular tank concept. Research should be conducted on other concepts. There is no reason to believe that present concepts produce the most efficient structures.

Materials Technology

The expanding technology of materials holds great promise of making materials available that will have exceptional properties. Development of physical and mechanical properties of all materials which have not been adequately studied for the cummulative effects of prior exposure to new environments and strain histories should be continued. Synergisms resulting from multiple environmental elements require special attention.

The establishment of structural design approaches for the utilization of brittle materials is a continuing requirement. Design approaches to the attachment and joint problem are of prime importance.

Many existing materials await structural application. The extraordinary properties of whiskers have not been exploited. Even though they are beyond the laboratory curiosity stage, they still have not been incorporated into useful load-carrying structural components. Other examples include utilization of ablating thermal protection systems as structural load-carrying members. Several ablating heat-protection schemes have been used for a number of years, but as yet little use has been made of the ablating material as a load-carrying structure. Use of the solid propellants as a stabilizer of motor case structures has hardly been explored.

It is obvious that the strength-density ratios of filament-reinforced materials can be several times greater than can be hoped for in the metal alloys. The technology of filament reinforcement is still in its infancy and many improvements can be expected. Ways must be found to take full advantage of these potentials.

Varying filament geometry to alter apparent density or reduce permeability by providing for denser filament packing is an area requiring investigation. Also needed are investigations of new filament materials, such as improved glasses and certain metal oxides, with the goal of providing greater strength and higher values of Young's modulus. Increase in Young's modulus is especially important and must be improved along with increased fiber strength, or the advantage of the increased fiber strength is diminished. Any such investigations naturally would require concurrent research on various filament-matrix combinations in order to realize the improvements gained from the filament research.

Of the unexploited metallics, beryllium, boron, and conceivably calcium appear to offer the most promise for the future. The "apparent" potential of beryllium is yet to be realized except for some heat-sink applications. Beryllium is a material which will probably find general usage in space vehicle structural applications very early in the time period of interest here. A strong effort should be made to exploit beryllium for use in primary structures, and to take advantage of its potential as a radiation shielding material and an efficient meteoroid bumper. Space vehicles appear to offer an economic field for its use as structure.

In the hard vacuum of space, faying surfaces may weld and lubricants may evaporate or sublime. The determination of material combinations best suited for intimate contact and the development of lubricants that are stable in a vacuum require continuing study.

Intermetallic compounds appear promising as superconductors and such materials will find application, for example, in active shielding in the form of magnet wire. Such compounds should be evaluated for highest critical magnetic field. Subsequently, research should be conducted on techniques for producing wire or other forms from promising compounds.

Thermal insulation is another fertile field in materials research. Effective insulation materials are required for the temperature range of from near absolute zero to near the melting point of most refractory materials. In the low-temperature range insulation may be required to be in contact with liquid hydrogen or helium and remain reasonably flexible.

Thermal control for liquid hydrogen tanks becomes so important that it can greatly influence the basic vehicle design. For boost vehicles conductive types of insulation are probably adequate. Internal insulations must remain stable and impermeable to liquid hydrogen at pressures in excess of 50 lb/sq in. and be strain compatible with the external structure. External insulation must be sealed to prevent condensation of the surrounding air. Research is required to produce effective insulation materials and sealing methods that are effective for the thermal and mechanical strains that will be encountered.

For space vehicles the insulation problem is even more severe due to the long periods of time involved. Multilayer, reflective insulation systems, because of their higher effectiveness, are more useful for this application than conductive types of insulation. There are several reflective types of insulation available at present; however, all have serious drawbacks wherein research efforts could materially improve their performance.

The transition between ground and space poses serious problems for reflective-type insulations. Vacuum jacketing the insulation for ground operation to prevent condensation of the surrounding air requires building and maintaining a vacuum-tight system. In addition, the compression of the insulation from external pressures on the vacuum jacket increases the thermal conductivity of the insulation by orders of magnitude and there is little assurance of uniform expansion of the laminae with release of the external pressure after launch.

The alternative of purging the insulation with helium while on the ground involves severe problems in venting during launch and outgassing in space. Expansion of trapped gasses could even ruin the effectiveness of the insulation.

At the other end of the temperature scale, insulation material may be called upon to insulate certain nuclear reactor parts where gas temperature may exceed 4,000° F with very high dynamic heads. Requirements for other materials could fall anywhere between the extremes mentioned.

Another requirement in nonmetallic materials is for electrical insulation for use in electrical propulsion schemes. This insulation must be stable, both chemically and physically, in a temperature environment of the order of 2,000° F, and still maintain high dielectric strength.

The materials constituting a space vehicle may be called upon to perform the functions of load-carrying members, and as shielding against meteoroids, nuclear radiation, electromagnetic radiation, and heat. At the present level of the technology each of these functions is accomplished by essentially independent shells. By coalescence of these shells into multipurpose units, greater structural efficiency will be achieved. This will involve a combined effort of materials-structural research, the ultimate goal being a multipurpose single shell in which the individual functions are indistinguishable. The closer this goal is approached, the greater will be the structural efficiency. In any event, unless the trend toward piling layer upon layer is revised, shield weights are going to become prohibitive.

Fabrication Techniques

Orbital assembly of space stations and repair of space vehicles must be well developed by the beginning of 1970. It will be difficult in many instances to provide for orbital assembly of space vehicles using purely mechanical attachments. Overcoming these problems will require the development of self-locking devices for remote assembly, learning of in-space welding techniques, and establishing techniques for the repair of micrometeoroid and other punctures. Self-repairing structures are highly desirable as a protection against the micrometeoroid hazard. Self-sealing liners for space structures are one approach. Provision for easy movement of equipment inside the space vehicle and rapid access to the damaged areas for repair is also necessary.

In-flight repair techniques, automatic or manual, will certainly be required for space missions of long duration. Methods must be developed to replace and repair expendable or damaged elements of spacecraft structure. Punctures, cracks, and leaks must be detected and arrested before they grow to catastrophic proportions. Ablation-type heat shields and impact absorption landing systems must be capable of being replaced or refurbished before each mission and may require attention immediately prior to reentry to eliminate any damage that may have occurred in space.

In reusable nuclear rockets, residual radioactivity can be a serious landing and refurbishing problem. In critical parts of the structure even traces of certain elements may be intolerable for this reason. Production of high purity parts thus could require fabrication by processes such as vacuum or vapor deposition. Such processes should be explored as a possible method of producing structural components of high purity or exact composition. Another achievement of such research could be the fabrication of components of shape or material that is difficult to form by conventional techniques.

Advanced studies in forming, welding, machining, mechanical joining, and assembling of parts from advanced materials should be undertaken concurrent with materials development programs. Paralleling such work can appreciably reduce laboratory-to-flight lead time.

New fabrication techniques must be devised that will allow the efficient joining of dissimilar metals. These applications will find use in the shielding necessary for protection against the wide range of space environments. Various metal alloy systems may then be fabricated into a composite shield structure.

"Canning" of fuel elements into desirable configurations offers challenges in fabrication. Fuel elements for advance nuclear rockets must be made of refractory materials built into desirable configurations and loaded with a nuclear fuel. For heat-transfer purposes, special configurations such as honeycombs or concentric rings are desirable. Tungsten is one of the most promising canning materials for use in fuel elements; however, much forming and joining research is needed before this material can be used satisfactorily in this application.

Similarly, refractory metals can be used to advantage in rocket nozzles if satisfactory fabrication techniques for this application can be devised. For such applications, operating temperatures of the order of 4,500° F may be a design requirement.

Research is being directed toward gaseous cavity reactors for nuclear rockets. Pressure in the cavity may be in hundreds of atmospheres and temperatures in excess of 10,000° F may be experienced in this device. The feasibility of this concept depends on the solution of the material application and structural design concepts for nozzles and reactor containers.

The physical size of vehicles envisioned for the time period of interest to this report will pose numerous fabrication problems. Present-day dimensions are taxing transportation facilities. Some of the future vehicles will require on-site fabrication. Fabrication or assembly in the field will require development of new techniques.

The potential savings in recovering and refurbishing large boosters and space vehicles dictate a continuing effort to solve the technical problems in a fashion that minimizes the cost of refurbishment and reuse.

Expandable and Erectable Structures

Many potential applications for large extremely lightweight space and reentry structures can be envisioned. A great many structures must be launched in a folded configuration and then unfolded after being positioned in space. The deployment methods will vary with the application. Inflatable fabric and foldable and erectable metallic elements appear suited to these applications.

Fabrics for high-temperature applications are under development. Evaluation of their application as auxiliary, deployable, lift and drag devices for reentry vehicles and recovery capsules should be a continuing effort.

The erection-in-space problem of large space radiators is a particularly complex task. Liquid-metal leaks cannot be tolerated and rotating seals are generally not acceptable. The radiator must be pressure-tight (probably of all-welded construction), necessitating the bending of metal parts, including liquid-metal filled tubes, during deployment in space. Methods must be provided either for keeping the metal within the radiator in the liquid state while it is being deployed or for thawing it after deployment, prior to engine startup.

The most promising materials for these radiators, from a weight and heat-transfer viewpoint, are beryllium, beryllium oxide, pyrolytic graphite, and molybdenum, in the order listed. The ideal radiator structure would probably be composite in construction with a liner made of a refractory material that is compatible with the internal working fluid. Fabrication research is required to develop methods of building large composite radiator structures that are deployable and reliable.

For manned vehicles using a nuclear reactor power source, shielding weight can be reduced by providing large separation distances (possibly hundreds of feet) between the reactor and the crew. Research is required in developing practical minimum weight structures that can provide this separation.

Design and construction of all types of base facilities on the moon present numerous structural problems. Designs are complicated because of the radically different moon environment; namely, reduced gravity, negligible atmosphere, large temperature changes, meteoroid impact, and ionizing radiation. Costs and limitations of transportation to the moon require maximum compactness of the structures during transit, and maximum use of native lunar materials in construction, maintenance, and substance. New techniques must be developed for lunar construction, such as soil movement by use of controlled energetic materials (e.g., explosives), automatic welding with exothermic processes, and self-erection of structural systems.

Lightweight expandable structures of the type employed by the Echo satellite will become more complex. A typical example is the direct nuclear electrogenerator envisioned for uses in space. This structure will probably consist of two concentric spheres made of foil, the diameter of the larger sphere being of the order of 30 to 80 feet. The inner sphere will be coated with a radioisotope emitting alpha or beta particles. Because of the difference of potential between the two spheres, electricity will be generated. Electrostatic forces will tend to collapse the outer sphere. The unique structural problems associated with a structure of this type are deployment of the structure after launching, maintaining the desired configurations during operation, and providing for any dissipation of energy that may be required prior to deployment of the system in space.

Design of lunar alighting gear is greatly dependent upon the nature of the lunar surface. If the lunar surface is composed of thick layers of soft dust, an alighting gear of unusual properties will be required. To avoid obscurement of the landing by the dust cloud raised by the engine retrothrust, and to avoid burrowing into a hole, it may be necessary to free-fall the landing module from a considerable height. This will probably require an expandable landing gear having large horizontal surface areas cantilevered outward from the craft so as to provide stability, absorb energy, and carry impact loads to the landing vehicle.

CRYOGENIC STRUCTURES

Much has been accomplished in increasing the knowledge of the design of cryogenic pressure vessels but there is still much to be done. Far too little is known about crack propagation and its relation to notch sensitivity, especially at very low temperatures. Unfortunately, even less is known about what to do about it. The approach of categorically rejecting as unsuitable those materials which are notch-sensitive is not necessarily the best one. There should be structural solutions to the problem rather than relying only on material selection. Can the crack-stopping techniques of the pressurized aircraft fuselage contribute at all? If not, why not? If so, in what regimes?

The cryogenic problem may be even more acute as use of liquid-helium-cooled devices becomes more prevalent. Applications relying on superconductivity are on the increase. Some of these applications, such as active radiation shielding, induce high loads on supporting structure. Accordingly, investigation of material and structural behavior needs to be extended to the near-absolute-zero temperature range. In such an extension, some unexpected phenomena may be expected.

A large potential weight saving is possible if tanks can be built from filament reinforced plastics. This construction however is permeable to gases, necessitating the use of a sealant or liner. At the temperature of liquid hydrogen, few, if any, materials are presently available that are both impermeable and compatible with the large strains that filament reinforced plastic vessels exhibit. Research is required to develop suitable materials or sealing techniques that can seal liquid hydrogen and oxygen tanks and can still withstand high strains for a substantial number of pressure cycles. An alternate, and possibly more feasible approach to this strain compatibility problem for filament wound structures would be the development and use of high modulus fibers that would be compatible with metal liners. Boron fibers provide a possible solution.

Under zero gravity conditions, the transfer of cryogenic liquids requires a positive expulsion device and means of keeping the liquid separated from the gas. Devices considered include piston arrangements, bellows, and flexible bags. The use of capillary force methods for collecting propellants in the "zero-g" state is another technique worthy of investigation. Operations of these devices are complicated by the low temperature at which they are required to function. Development of satisfactory expulsion systems must be accomplished, however, if many planned missions are to be fulfilled.

PERMANENT MANNED SPACE STATIONS

The pursuit of a logical space program will require the establishment and maintenance of manned space stations on a permanent basis. Before this can be accomplished, a number of structures and materials problems remain to be solved. One of these is the development of design concepts and materials systems capable of providing adequate environmental protection over extended time periods. These systems must also be capable of being transported and erected at the desired location in space. Repair of environment-caused damage (due to meteoroids, for example) will be a significant consideration, as will be the requirements for supply and crew relief on a routine basis.

A number of serious problems are anticipated in space station dynamics including the requirement for provisions of artificial gravity, rendezvous, and docking. Artificial gravity may be provided by flexible bola-like systems using cables and counterweights, or in rigidized systems such as the rotating wheel concept. There are many interesting cable-dynamics problems associated with the use of the flexible system. In either case, movement of the manned inhabitants will perturb the dynamic motion. Mass and momentum changes due to docking operations will further perturb the motion.

The rendezvous and docking problems include the development of energy-absorption devices to minimize energy transfer during docking maneuver and the effects of the space environment on seals of access hatches used for transfer of men and equipment.

REENTRY FROM SPACE

Despite major progress in recent years in solving the problems associated with atmospheric reentry, major problems remain. In the next decade reentry velocities of 50,000 ft/sec or higher may be experienced. Entry at higher than circular orbit velocities (desired for many space systems) results in a heating environment different in nature and magnitude from the suborbital case. Thermal protection systems are today, and will remain in the future, a significant fraction of reentry vehicle weight. Major performance improvements in these protection systems are important in reducing total system size and cost. The problems of entry into other planetary atmospheres need to be examined in more detail and better defined with the same purpose in mind.

Continuing development in the areas of hot structures for orbital and superorbital reentry is required. Special attention must be paid to the structural design of hot spots such as nose caps, leading edges, and control surfaces. The combination of the thermal shield and supporting structure into one efficient structural system is desirable here also.

The present approach to this problem as exemplified by the X-20, Mercury, and Gemini, is to provide an outer structure to resist heating and local loads and another inner structure for primary loads. Evaluation of the true seriousness of the effects of thermal stresses and deformations if only a single structure were used (perhaps even a new structural concept) is required, perhaps even overdue.

The development of an efficient operational transpiration cooling system may be one approach to hot-spot protection for reusable reentry vehicles. A satisfactory system should also find many applications for structural elements which are required to maintain precise geometry under very high-temperature environments.

TEST TECHNIQUES AND FACILITIES

The problem of proving the acceptability of spacecraft structures before they leave the factory will become increasingly difficult as the size of vehicles grows and the environmental factors to be simulated multiply.

A key technical problem to be solved before many of the future steps in space exploration can be taken is the simulation of the space environment and its effects on structures and materials as well as on other system elements. This is particularly acute in the detection of synergisms. Adequate techniques for ground simulation will be needed to investigate design solutions to environmental and interaction problems. Ground simulation facilities, for example, are still far from the goal of providing for all significant features of the heating environment. This problem alone will require a significant research effort over the next several years before an adequate technology is developed.

Test evaluation methods to demonstrate structural integrity and give proof of compliance with mission requirements and strength analyses are going to become not only more expensive but also more complicated. There will be great pressure on the structural-test and materials engineer to devise test techniques for evaluating complex environments with simple, short-time test programs. At present, there is no reliable short-time test method that will simulate long-time behavioral characteristics of a structure. If meaningful tests are not developed or long-time tests included in future planning, this gap in the technology will become dangerous.

Many new test techniques and procedures must be developed. Tests combining temperature, radiation vacuum, load, vibration, etc. must be evaluated. The importance of simultaneous environment exposure and detailed mission-sequence simulation must be determined. Similarly ground simulation of dynamic effects for large space vehicles will be nearly impossible to accomplish in full-scale tests. Critical combinations must be determined and key parameters in model or subscale simulation must be defined.

Facility capability must also stay abreast of test requirements. At present, ground facilities cannot satisfactorily simulate reentry heating for structural test purposes. In a very short time, payload weights will exceed the available capabilities of shakers for full-scale vibration tests. New facilities must be developed or new design concepts must be evolved that do not rely on final testing for assurance of reliability.

At present, many test facilities are constructed to accomplish a specific task and are dismantled on completion or redesigned for other jobs. With the size and complexity of structures visualized for the Nova class and larger launch vehicles, test facility costs become too great for such destruction or duplication to be tolerated. Only a limited number of such facilities are really required, and judicious planning could result in stands that are universal in application to vehicles.

Mainly because of transportation difficulties, actual construction of some large launch vehicles at the launch site is visualized. The facility for this could serve the multiple purpose of construction jig, test facility, and launch platform. Much planning will be required to achieve this ultimate usefulness, but economic considerations will eventually dictate such a policy.

SYSTEMS HARDENING

The military implications of operations in space, at this time, are imponderable. It is possible to assume, however, that within the next 10 to 15 years, space vehicles will assume a military role and counterweapons will have advanced substantially. The destruction or neutralization of satellites, orbital space stations, supply vehicles, and other military space vehicles will inevitably become a requirement if and when space vehicles assume a military role.

Resistance to the effects of blast, gas clouds, particle penetration, and radiation will all be considerations in the hardening of space vehicles, as will be the production of countermeasures. In anticipation of these advances, research needs to be begun which will reduce vulnerability to countermeasures. Better understanding is needed of the methods of designing a structure resistant to various types of impact, hypervelocity particle impact, thermal impact, and blast.

The continued effectiveness of missile systems as a deterrent force will depend in large part on the development of systems with a high "effective" hardness so as to be capable of retaliation after absorbing an initial surprise attack. "Effective" hardness is a broad term, which may include dispersion and/or reliability, besides the ability immediately to survive the effects of weapons. Major structural and materials problems are involved in providing, at a reasonable cost, direct hardness of underground structures that are capable of withstanding attack by weapons with destructive powers of the order of megatons.

Examples of such problems would include determination of the shock transmission characteristics of various types and combinations of soils, the response of various types of structures to shock and other countermeasures, and the minimizing of damage to system components within the missile.

Conversely, if this increased hardness is achieved, the continuing effectiveness of weapon systems will depend, in part, on increasing the lethality of the warhead. This imposes severe technical requirements on reentry body design. Among these are: (1) special design configuration, (2) thermal protection systems that present a minimum radar cross-section area, (3) design of reentry vehicle structure to resist the effects of defensive weapons, (4) design to accommodate antennae needed for countermeasures, guidance, etc., (5) design of vehicles with earth penetration capabilities. The achievement of this effectiveness will necessitate major achievements in structures and materials technology.

CONCLUDING REMARKS

An estimate has been made of the general operational requirements of future missile and space systems in terms of launch operations, manned operations in space, and reentry from space. These operational requirements provide a framework for the identification of the structural problem areas requiring research efforts to provide the required technology for design of future missile and space vehicles. It is significant to note that launch systems have received less emphasis than the space and reentry systems, primarily because of this nation's significantly higher level of experience with launch vehicles.

No attempt has been made to assign priorities to these problems, for such priorities would depend on the time phasing of the operations and would change with time-shift changes. However, the most significant problem areas have been identified. These may be summarized as follows:

During the 1970 to 1980 period, major space efforts will include lunar exploration, establishment of space stations, and reconnaissance of Mars and Venus. These missions will require significant technological advances in the areas of nuclear power plants and/or electrical propulsion systems, construction and utilization of space stations, extraterrestrial vehicles and bases, orbital and reentry heating, communications systems, radiation shielding, and economic utilization of structures with regard to multipurpose usages.

It was further pointed out that in order to solve these problems, there will have to be concurrently significant advances in research methodology, materials technology, fabrication techniques, and test methods.

Throughout this report the emphasis has been placed on multipurpose structures, minimum weight structures, and structural weight compromise for maximum efficiency systems. It is felt that the trend in missile and space vehicle structures will continue to be toward simplicity and reliability, and that increasing emphasis will be placed on integration of the structures with other considerations to yield systems of the maximum cost effectiveness.

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